Assessing the Lagrangian Predictive Ability of Navy Ocean Models

PI: B. L. Lipphardt, Jr.
University of Delaware
Robinson Hall
Newark, DE 19716
phone: (302) 831-6836 fax: (302) 831-6521 email: brucel@udel.edu

CO-PI: A. D. Kirwan, Jr.
University of Delaware
Robinson Hall
Newark, DE 19716
phone: (302) 831-2977 fax: (302) 831-6521 email: adk@udel.edu

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LONG-TERM GOALS

Our long-term goal is better understanding of the processes that influence ocean transport at all scales. We focus on the sub-mesoscale and mesoscales because they represent the greatest challenge both for modeling and observing the ocean, since the ocean's response at these scales is both nonlinear and episodic. Our recent efforts emphasize the application of Lagrangian analysis tools to ocean velocity archives for studying transport processes.

OBJECTIVES

With prior ONR support, we have quantified many Lagrangian properties of synoptic ocean data archives, including both regional ocean models and coastal HF radar measurements. We have also explored the application of dynamical systems tools to study the Lagrangian properties of these archives. More recently, as we have compared observed near-surface drifter trajectories with those predicted from Navy ocean models, we've found that the typical Lagrangian prediction horizon for these models is no more than 24-48 hours. As Navy operators begin integrating Lagrangian forecasts into tactical decision aids for acoustic problems, the fidelity of these forecasts becomes crucial. Thus, we are motivated to quantify the uncertainty in Navy Lagrangian forecasts and develop new analysis products that communicate this uncertainty to fleet operators in an accessible way.

APPROACH

Our approach relies on analysis of ensembles of Navy operational model forecasts. We have ensemble forecasts from the Navy Relocatable NCOM (RELO) model for two geographic regions: Hawaii (32 ensemble members to support the RIMPAC-08 experiment) and Japan (24 ensemble members to support analysis of the LWAD-07 experiment). Both models have a horizontal resolution of 3 km. RELO ensembles capture the variability over the forecast period due to two likely sources of

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uncertainty, model initial state and wind forcing. Our first task was to describe the Eulerian variability among the ensemble members using traditional statistics over the forecast interval. In each region, the velocity mean and standard deviation was computed at regular intervals for all ensemble members. The velocity standard deviation ($\vec{v}_{STD}$) is defined here as:

$$\vec{v}_{STD} = \sqrt{u_{STD}^2 + v_{STD}^2}$$

To assess the Lagrangian variability among ensemble members, 72 hour trajectories were computed for particles launched at each grid point at a depth of 12.5 m for each ensemble member. To ease the comparisons with the Eulerian velocity statistics, the launch location ($\vec{x}_o$) and final position ($\vec{x}_f$) for these 72 hour gridded trajectories were used to compute a mean Lagrangian velocity ($\vec{v}_L$), defined as:

$$\vec{v}_L = \frac{\vec{x}_f - \vec{x}_o}{\Delta t}$$

Gridded trajectories (both forward and backward in time) were also used to construct daily direct Lyapunov exponent (DLE) maps for each ensemble member in both geographic regions (see Haller, 2001 for details). Two methods of "averaging" to construct a single representative DLE map from the ensemble velocity fields were compared: (1) taking the mean of all individual ensemble member DLE maps, and (2) computing a single DLE map from the ensemble mean velocities (time-dependent velocity field computed from the instantaneous mean of all ensemble members).

Finally, to visualize the character of the ensemble variability in the Hawaii region (where the mesoscale field is typically very energetic), circular fluid blobs were evolved over a ten-day period using instantaneous velocities from four randomly selected ensemble members as well as the ensemble mean velocities.

WORK COMPLETED

The following tasks were completed during this performance period:

- With help from NRLSSC, a 24 member ensemble of Navy RELO model forecasts was computed for the October 2007 period when 30 SVP drifters were launched north of the Kuroshio as part of the LWAD-07 experiment.

- A search of the Global Drifter Program data archives yielded no additional drifters in the LWAD-07 region that could be used to augment the 30 drifters launched as part of the experiment.

- For each ensemble member, 72 hour trajectories were computed for particles launched at every model grid point at a depth of 12.5 m. These 72 hour trajectories were reinitialized daily over the first ten days of the drifter observations.

- Ensemble Eulerian velocity statistics (mean and standard deviations) were computed at a depth of 12.5 m over the first ten days of the drifter observations.

- Ensemble Lagrangian velocity statistics were computed at a depth of 12.5 m using particle displacements over a period of 72 hours. These statistics were compared with the Eulerian velocity statistics.

- Direct Lyapunov exponents (DLE) were computed for each RELO ensemble member in the Hawaii and Japan regions. Two methods for combining ensemble DLEs (averaging all individual ensemble DLE maps versus computing a single DLE map from the ensemble mean velocity field) were compared.

- Ensembles of fluid blobs were evolved using RELO velocities around Hawaii to help visualize the Lagrangian variability in the ensemble velocity archive.

RESULTS

Example Eulerian velocity statistics for the RELO Japan region ensembles at 0000 UT, 18 October 2007 are shown in the upper panel of figure 1. The color contours show $\vec{v}_{STD}$ with ensemble mean velocity vectors overlaid. This example is typical, and shows several regions (colored red) where the magnitude of the velocity standard deviation is comparable to that of the velocity mean. These regions often correspond to areas with energetic mesoscale variability. Note that the standard deviation describes the variability *among ensemble members* at a *single instant in time*, indicating that the model's description of these mesoscale features (strength and location) is often uncertain. Since the model resolution is quite good (3 km), this uncertainty most likely stems from a lack of constraining observations (assimilated into the model) at these scales.

These Eulerian ensemble velocity statistics can be compared with the Lagrangian ensemble statistics shown in the lower panel of Figure 1, for gridded trajectories launched at 0000 UT, 18 October 2007. Regions with high Lagrangian velocity standard deviations correspond with regions having high instantaneous Eulerian velocity variability, as might be expected. The example ensemble trajectories overlaid on the lower panel of Figure 1 clearly show that the model represents the strength and location of the Kuroshio very consistently, while the details of the mesoscale field southeast of the Kuroshio vary markedly among ensemble members. Note also that the Eulerian and Lagrangian velocity standard deviations are comparable, and that the ensemble Lagrangian variability produces particle separations exceeding 100 km among ensemble members after 72 hours. Ensemble Lagrangian uncertainties of this magnitude could account for differences between model and observed trajectories (mean separation of 46 km after three days, using the EAS16 model) for 29 drifters launched as part of the LWAD-07 experiment.

A similar Eulerian versus Lagrangian velocity statistics comparison for the RELO region around Hawaii at 0000 UT on 19 July 2008 is shown in Figure 2. As with the Japan region, although the model resolution is very good (also 3 km), and the ensemble members show a good deal of variability in the mesoscale velocity field, with standard deviations again often approaching the same magnitude as the mean velocities. Throughout most of the domain, example ensemble trajectories confirm the uncertainty in the mesoscale field, with particle separations often exceeding 100 km after 72 hours among ensemble members.

DLE fields depict regions of rapid particle separation in both forward and backward time, and typically clearly delineate the boundaries between mesoscale features like eddies and jets. Two methods for

constructing an ensemble mean DLE field for the Hawaii region for July 10, 2008 are compared in Figure 3. The top panel shows the DLE field constructed using the ensemble mean velocities. The bottom panel shows the mean of 32 individual ensemble member DLE fields. Figure 3 (bottom panel) shows that the large mesoscale fluctuations among ensemble members enhance the small-scale DLE structure when individual DLE maps are averaged. While the DLE field computed from the ensemble mean velocities is smoother, it is not clear that a DLE field with suppressed small-scale variability is the "best" representation of this ensemble dataset. Further analysis is required to explore the importance of these differences.

To visualize the impact of ensemble variability over time, two groups of five fluid blobs were launched in the RELO region around Hawaii on July 2, 2008 and allowed to evolve over ten days. Figure 4 shows three snapshots of these blob groups, at launch time (upper panel), after five days (middle panel) and after ten days (lower panel). In each blob group, the yellow blob was evolved using the ensemble mean velocities. The four other blobs were evolved using four random ensemble member velocity fields. Both blob groups demonstrate that, while small-scale details of the evolving flow can differ significantly among ensemble members, a larger-scale flow structure persists among them. Aspects of this larger-scale flow can be seen in DLE maps (not shown). This visualization suggests that, even if smaller scales are poorly constrained by assimilated data, the evolving larger-scale Lagrangian structure may be preserved by the ensemble set.

IMPACT/APPLICATIONS

As part of a related project (*N00173-08-1-G009,* see below) we are developing Lagrangian analysis tools to be incorporated into Navy acoustic tactical decision aids. This development has identified a critical need for uncertainty metrics to accompany these Lagrangian products. Even crude estimates of Lagrangian uncertainty are difficult to obtain directly from archives of Eulerian model velocities. The ensemble Lagrangian uncertainties developed as part of this effort will provide fleet operators with a robust metric. In addition, these metrics will give modelers new insight into how their Eulerian uncertainties ultimately impact trajectory predictions over time scales of tactical interest to the Navy.

RELATED PROJECTS

The investigators for this effort are also the principal investigators on three other closely-related ONR efforts:

N00014-09-1-0703: How well do blended velocity fields improve the predictions of drifting sensor tracks? – This project explores two different methods of data blending and their effectiveness for improving trajectory predictions. Since trajectory predictions underlie all other Lagrangian analyses, enhancing their accuracy is immediately relevant for all applications of Lagrangian forecasts.

N00014-07-1-0730: Enhanced ocean predictability through optimal observing strategies – This effort strives to apply synoptic Lagrangian tools to a regional ocean model off the coast of northern California as a proof of concept exercise demonstrating how knowledge of the evolving ocean might aid fleet operators concerned with optimizing AUV deployments in the coastal ocean.

N00173-08-1-G009: Prediction of evolving acoustic sensor arrays – This effort is focused on demonstrating how Lagrangian analysis of Navy ocean model predictions can be performed at a Navy

operational center and how Lagrangian products can be delivered to fleet operators on scene in near-real time to support tactical decision making.

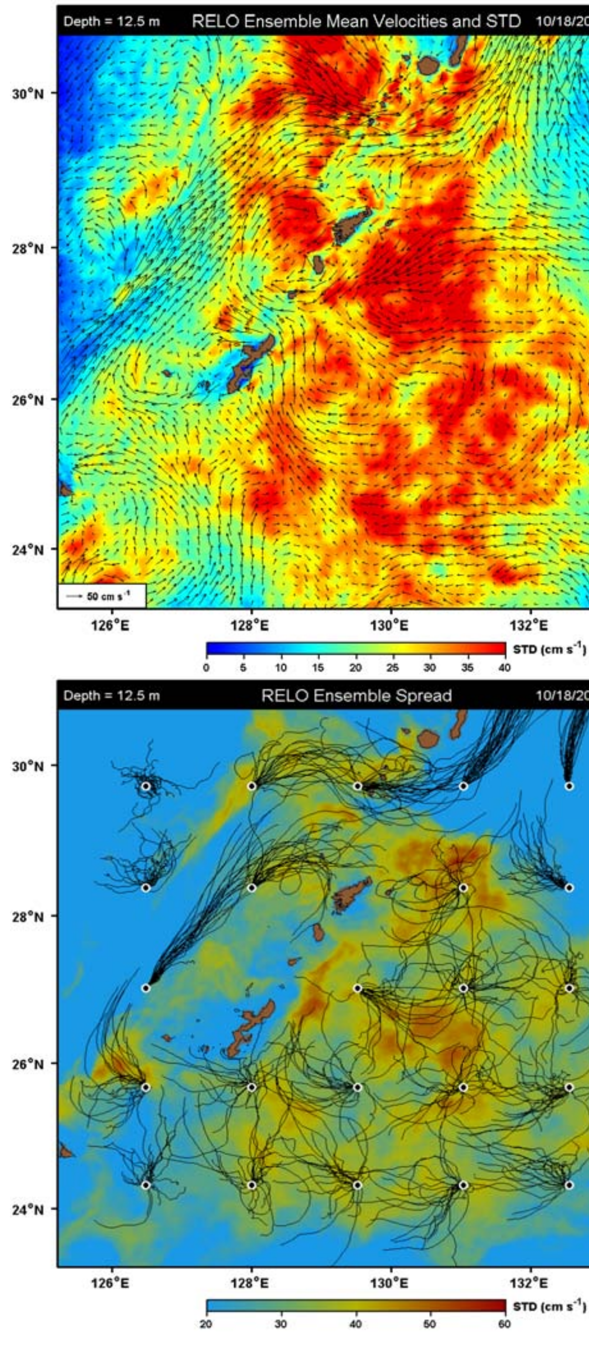

Figure 1: Color map of the standard deviation of velocity among 24 RELO model ensemble members for the region around Japan at 0000 UT on 18 October 2007 (top) with ensemble mean velocity vectors overlaid. At the bottom, color map of the standard deviation of Lagrangian velocity (for trajectories computed over 72 hours) for particles launched at 0000 UT on 18 October 2007 are shown, with representative ensemble trajectories (black) overlaid. Both results are for a depth of 12.5 m.

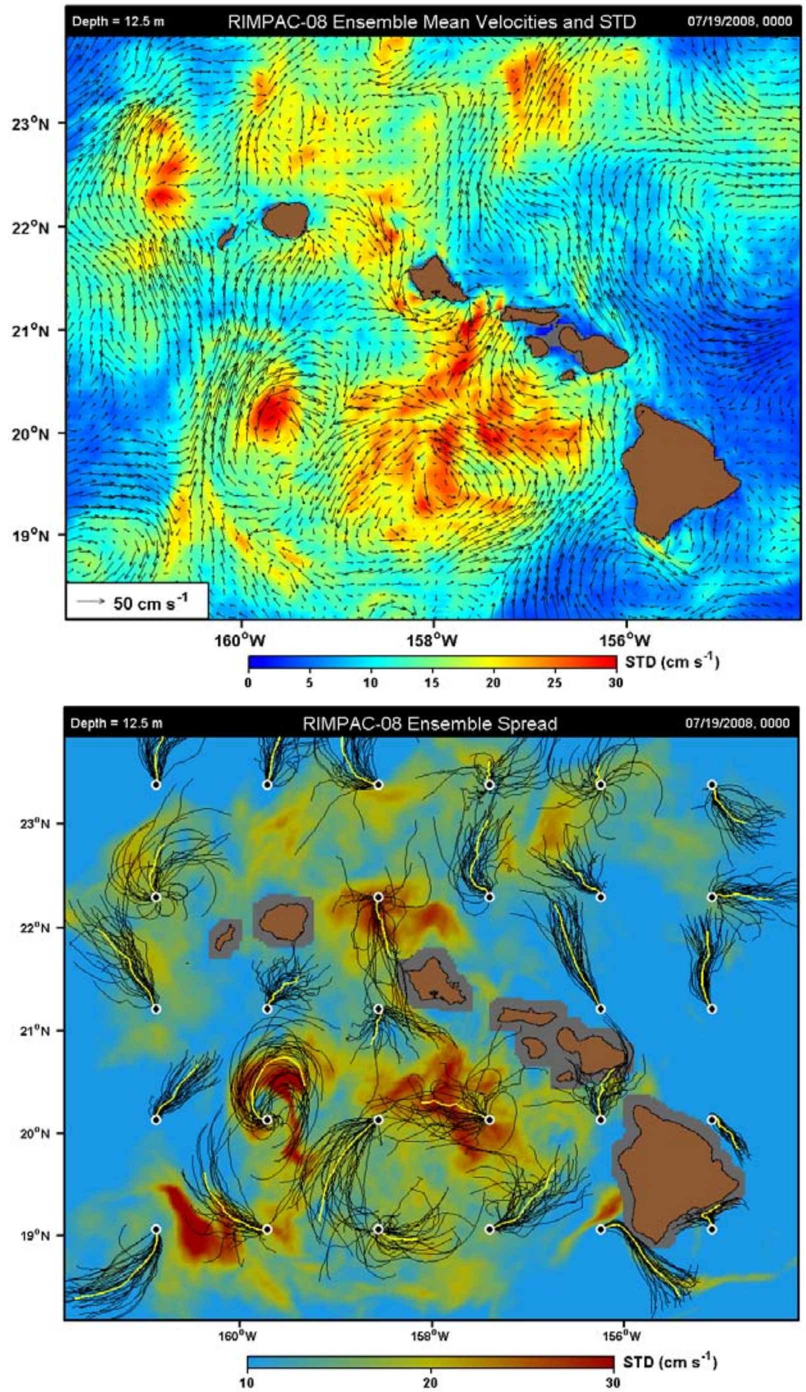

Figure 2: Color map of the standard deviation of velocity among 32 RELO model ensemble members for the region around Hawaii at 0000 UT on 19 July 2008 (top) with ensemble mean velocity vectors overlaid. At the bottom, color map of the standard deviation of Lagrangian velocity (for trajectories computed over 72 hours) for particles launched at 0000 UT on 19 July 2008 are shown, with representative ensemble trajectories (black) and trajectories computed using ensemble mean velocities (yellow) overlaid. Both results are for a depth of 12.5 m.

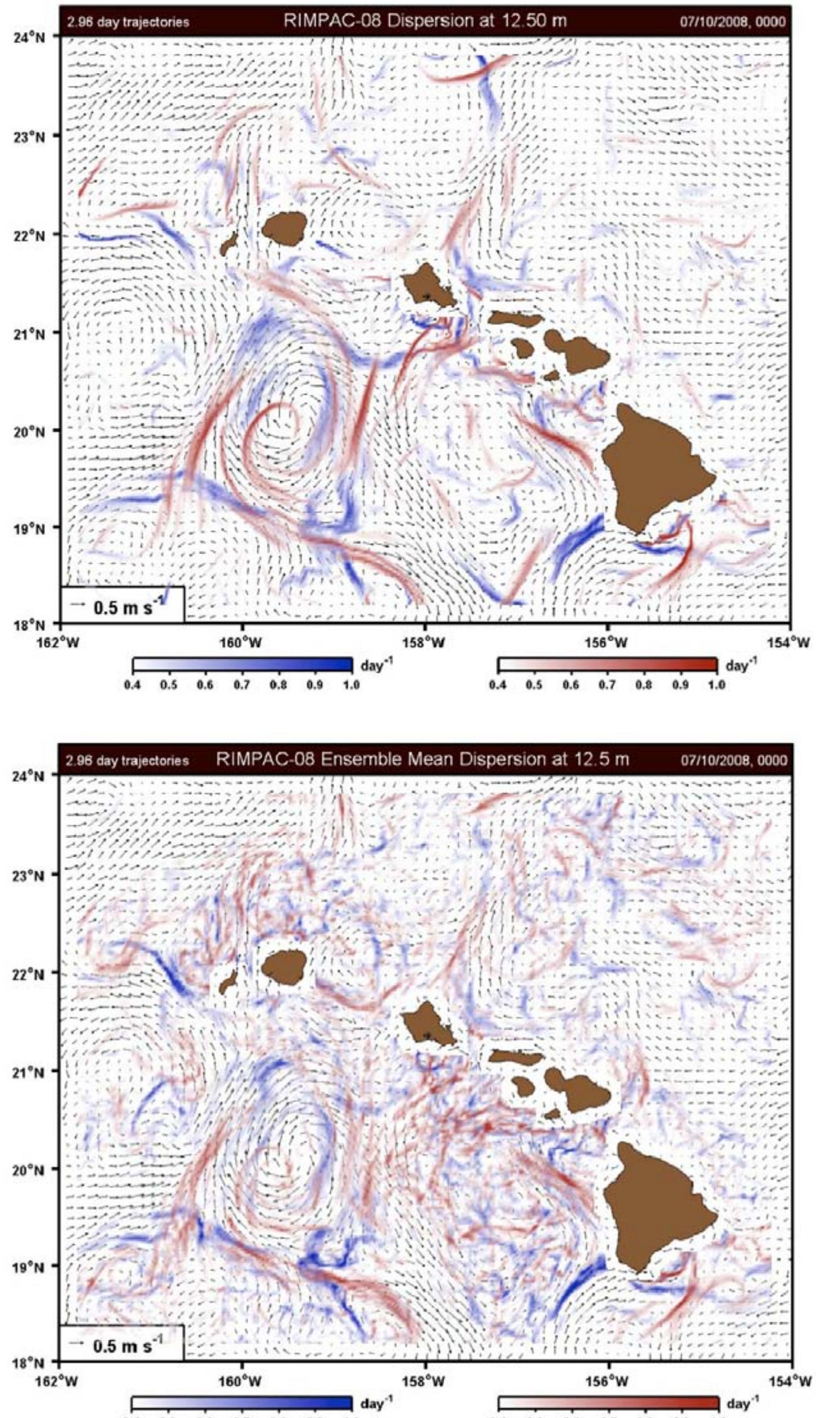

Figure 3: Comparison of two methods for computing mean DLE fields from 32 RELO ensemble members for the Hawaii region at 0000 UT on July 10, 2008 at a depth of 12.5 m. The top panel shows the DLE field computed from the ensemble mean velocity field. The bottom panel shows the mean of 32 ensemble member DLE fields. Red (blue) curves describe regions of rapid particle separation in forward (backward) time.

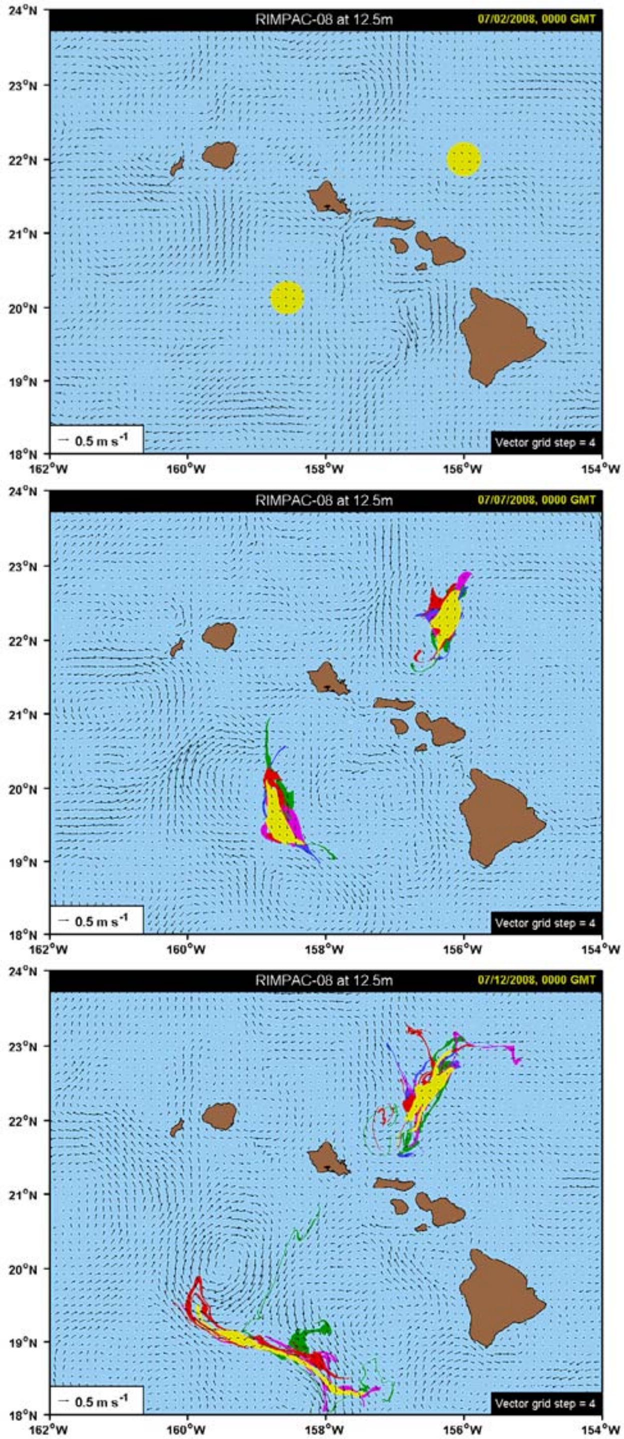

Figure 4: Evolution of five realizations of two blobs around Hawaii over ten days, predicted from 32 RELO model ensemble members at a depth of 12.5 m. Blobs evolved using ensemble mean velocities are shown in yellow. Other colored blobs represent evolution of the same blob using velocities from four random ensemble members. Blob positions are shown at midnight UT on 2 July 2008 (top), 7 July 2008 (middle) and 12 July 2008 (bottom).

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